Advancing Underwater Acoustic Communication for Autonomous Distributed Networks via Sparse Channel Sensing, Coding, and Navigation Support

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LONG-TERM GOALS

The long-term goal is to significantly advance underwater acoustic communication technologies for autonomous distributed underwater networks, through innovative signal processing, coding, and navigation algorithms. Providing highly reliable and high data rate communication links will be critical towards the development of a new era of underwater distributed networks.

OBJECTIVES

We have three objectives in this project.

1. **Advanced communication techniques of sparse channel sensing and nonbinary LDPC coding.** Underwater acoustic channels are naturally sparse, but how to effectively exploit the sparsity is a challenging task. We will investigate the recently developed "compressive sensing" algorithms for sparse channel estimation in the context of multicarrier acoustic communications. On the other hand, channel coding is one integral part of an advanced communication system, and is dispensable in approaching the theoretical limit predicted by the Shannon theory. We will thoroughly investigate nonbinary low-density-parity-check (LDPC) codes, and especially pursue fast encoding and decoding algorithms and practical implementations.
2. **High-resolution ranging and navigation.** Wideband multicarrier waveform has a dual use that it can yield precise timing information for the receiver to infer the distance from the sender. With range estimates from multiple buoys, each underwater vehicle can self localize and navigate. We will investigate ranging and tracking algorithms that achieve high positioning accuracy. We aim to integrate the communication and navigation capabilities into the OFDM modem under development, which will greatly facilitate the development of emerging underwater distributed networks.

3. **Testbed development and medium access control.** We plan to develop a network testbed to illustrate the cooperative networking scenario. We first will determine an effective medium

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access control protocol to improve the system throughput for multiple users equipped with high-rate OFDM modems. We will then carry out demonstrations in three settings: 1) point to point links with advanced communication techniques; 2) ranging and navigation in a setup with four buoys and one underwater node; and 3) cooperative networking in a setup with four buoys and multiple underwater nodes.

APPROACH

Our technical approach is to develop advanced signal processing algorithms to improve the robustness and increase the data rate of underwater acoustic communication. Specifically, 1) we will use compressive sensing algorithms to exploit the sparsity nature of the underwater acoustic channels, 2) we will develop advanced capacity-achieving nonbinary LDPC codes to improve the error performance, 3) we will improve the localization and navigation performance through the use of wideband OFDM waveforms, which has much increased time-resolution for ranging purposes, and 4) we will investigate effective medium access protocols along with a testbed demonstration with multiple nodes.

WORK COMPLETED

In this final year, we have continued to refine advanced receiver algorithms, with real data sets from experiments done in previous years. We have also conducted local tests in the Mansfield Hollow Lake near the UCONN campus.

After two years of preparation, our book on `` OFDM for Underwater Acoustic Communications", John Wiley & Sons, was published in May 2014.

We have supervised seven undergraduate students into research through their senior design projects:

- Project: "Coordinated Command and Control of UUV," Duration: Fall13-Spring14, Team Members: Katherine Domrese, Shalini Khare, Matthew Maddocks
- Project: "Underwater Acoustic Communications Security", Duration: Fall13-Spring14, Team Members: Alivia Grate, Brandon Gilbert, Kaitlyn King, Muhammad Samir

RESULTS

We next highlight our progresses made on the following topics, arrranged in three different categories.

Receiver design:

1) Adaptive modulation and coding for underwater acoustic OFDM;
2) A Study on Pulse-Width-Modulation based Power Amplification for Underwater Acoustic OFDM

Channel and netowrk coding:

3) OFDM modulated dynamic coded cooperation in underwater acoustic channels;

Localization, Networking, and Testbed:

4) On-demand asynchronous localization for underwater sensor networks;
5) A sea test of mobile underwater localization

1)Adaptive modulation and coding for underwater acoustic OFDM. Adaptive modulation and coding (AMC) technique can be applied in underwater acoustic communications to improve the system data rate as well as the robustness in vary- ing channel conditions. In this work, we demonstrate an OFDM based AMC operation using a number of transmis- sion modes with different data rates. We propose to use the effective signal-to-noise ratio (SNR) computed after channel estimation and channel decoding as performance indicator for mode switching, instead of input SNR and pilot SNR. Real time AMC tests have been conducted in a recent sea experiment; see Figure 1.

2)A Study on Pulse-Width-Modulation based Power Amplification for Underwater Acoustic OFDM. In this work, we investigate the power amplification for underwater acoustic orthogonal frequency-division multiplexing (OFDM) systems. The maximum power delivery (MPD), and the pilot signal to noise ratio (PSNR) specific to the OFDM modulation, are adopted as design criteria. We study the impact of key parameters associated with the pulse width modulation (PWM), such as the modulation frequency, the number of quantization bits, and the input clipping threshold, and provide a suitable procedure to determine those parameters to increase the maximum power delivery while meeting a certain PSNR threshold. Experimental setup has been established, where the experimental results validate the key findings from the analytical and simulation results; see Figure 2.

3) OFDM modulated dynamic coded cooperation in underwater acoustic channels. Dynamic coded cooperation (DCC) allows relay diversity without altering the transmission procedure from the source to the destination. In this work, we propose a practical orthogonal-frequency-division-multiplexing (OFDM) modulated dynamic coded cooperation scheme for underwater relay networks, as shown in Figure 3, where OFDMmodulation accommodates multipath fading channels with large delay spread. Two cooperation strategies are studied, where the relay transmits either identical or different OFDM blocks as the source during the cooperation phase. The block-level synchronization between the OFDM blocks from the source and the relay is achieved by a delay control mechanism at the relay, by knowing the distances among the source, relay, and destination. Two OFDM-DCC design examples are presented, one based on nonbinary rate-compatible LDPC codes applied across multiple OFDM blocks, and the other using layered interblock erasure-correction and intra-block error-correction coding. In addition to simulation studies, one particular design has been implemented on practical OFDM modems, and tested in a swimming pool and in a recent sea experiment; see Figure 4. The proposed OFDMDCC scheme is particularly appealing to underwater acoustic networks where a relay node with abundant resources (e.g., a surface buoy) can enhance communications among underwater nodes without changing their transmission procedure.

4) On-demand asynchronous localization for underwater sensor networks. In this work we consider the issue of localization in the context of underwater sensor networks which contain anchor nodes with perfect knowledge of their position, but asynchronous clocks. By taking advantage of a sequential transmission protocol and the broadcasting nature of the acoustic underwater medium, the entire network can be localized simultaneously with small overhead. Additionally, it can be initiated by any node at any time. Through extensive simulation and derivation of the Cramer-Rao Lower Bound (CRLB), we first verify the utility and performance of the algorithm, demonstrating that both initiator and passive nodes can achieve low-error positioning. We then implement the algorithm on an existing

modem, and through tests performed within a pool and lake we have determined the accuracy and effectiveness of the algorithm in a true underwater environment; see Figure 5.

5)A sea test of mobile underwater localization. Localization and tracking of underwater moving objects are of great interest in many applications. This work presents a recent sea test on underwater localization carried out in the Sizihwan coastal area near Kaohsiung, Taiwan, May 2013, where three stationary nodes are used to localize one mobile node via acoustic communications based on orthogonal frequencydivision multiplexing (OFDM) modems. Experimental results show that the estimated trajectory of the underwater mobile node agrees well with the track recorded by global positioning system (GPS); see Figures. 6-9.

IMPACT/APPLICATIONS

The success of our project will have a deep impact. Providing high-data-rate and reliable acoustic communication with navigation functionalities, our project will directly contribute to the development of distributed autonomous underwater networks that are of great interest to Navy, e.g., the AUV/UUV/Glider networks.

PUBLICATIONS

Book:

1. S. Zhou and Z.-H. Wang, OFDM for Underwater Acoustic Communications. John Wiley & Sons, Inc., 2014. [published].

Papers:

1. P. Carroll, K. Mahmood, S. Zhou, H. Zhou, X. Xu, and J.-H. Cui, “On-demand asynchronous localization for underwater sensor networks,” IEEE Transactions on Signal Processing, vol. 62, no. 13, pp. 3337–3348, July 2014. [published].
2. L. Wan, H. Zhou, X. Xu, Y. Huang, S. Zhou, Z. Shi, and J.-H. Cui, “Adaptive modulation and coding for underwater acoustic OFDM,” IEEE Journal of Oceanic Engineering, 2014, DOI: 10.1109/JOE.2014.2323365 [In Press].
3. Y. Chen, Z.-H. Wang, L. Wan, H. Zhou, S. Zhou, and X. Xu, “OFDM modulated dynamic coded cooperation in underwater acoustic channels,” IEEE Journal of Oceanic Engineering, 2014, DOI: 10.1109/JOE.2014.2304254 [In Press].
4. Xiaoka Xu, Hao Zhou, Li Wei, Shengli Zhou, and Jun-Hong Cui, “A Study on Pulse-Width-Modulation based Power Amplification for Underwater Acoustic OFDM,” IEEE Journal of Oceanic Engineering , 2014 [submitted].
5. H. Gao, X. Xu, D. Huang, C.-F. Huang, T. Yang, W.-H. Twan, J.-Y. Liu, and S. Zhou, “A sea test of mobile underwater localization,” in Proc. of IEEE/MTS OCEANS conference, Taipei, Taiwan, April 7-10, 2014.
6. K. Mahmood, K. Domrese, P. Carroll, H. Zhou, X. Xu, and S. Zhou, “Implementation and field testing of on-demand asynchronous underwater localization,” in Proc. of the Asilomar Conference on Signals, Systems and Computers, Asilomar, California, Nov. 3-6, 2013.

7. L. Wan, H. Zhou, X. Xu, Y. Huang, S. Zhou, Z. Shi, and J.-H. Cui, “Field tests of adaptive modulation and coding for underwater acoustic OFDM,” in Proc. of the 8th ACM International Conference on UnderWater Networks and Systems (WUWNet), Kaohsiung, Taiwan, Nov. 11-13, 2013.

HONORS/AWARDS/PRIZES

Shengli Zhou was elected IEEE Fellow for ``contributions to wireless and underwater acoustic communications".

Dr. Zhaohui Wang won the outstanding woman scholar award from the Graduate School at the University of Connecticut, May 2014.

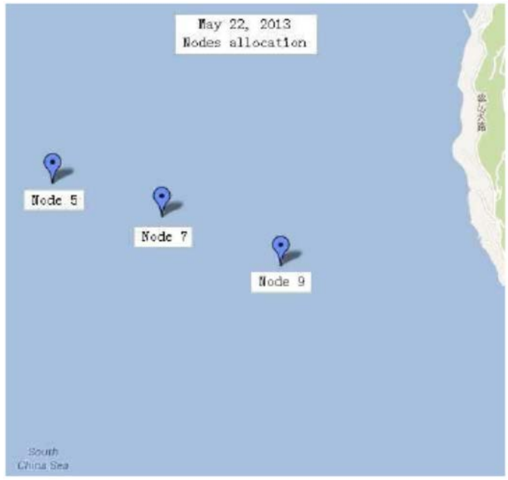
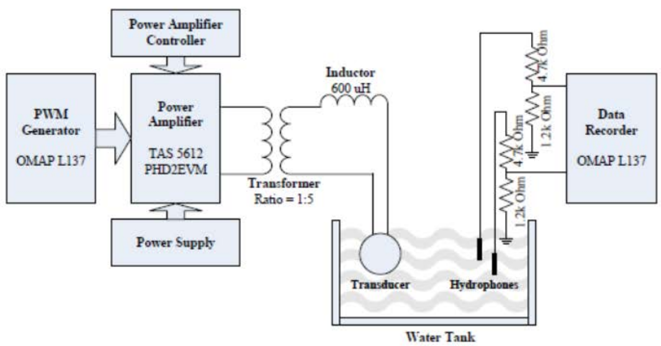
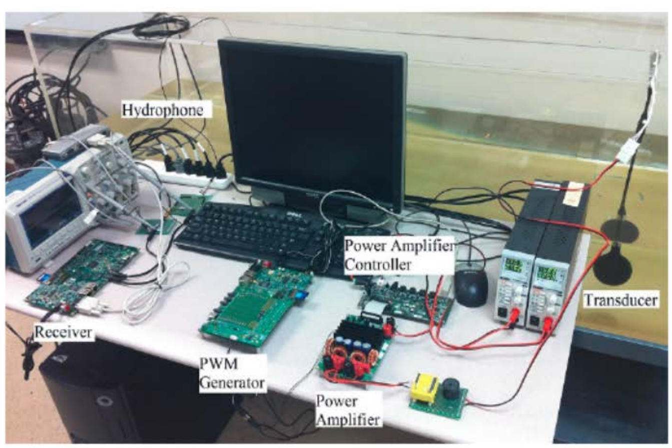


Figure 1: An adaptive modulation and coding (AMC) has been conducted in a sea experiment, near Kaoshiung City, Taiwan, May 22, 2013.

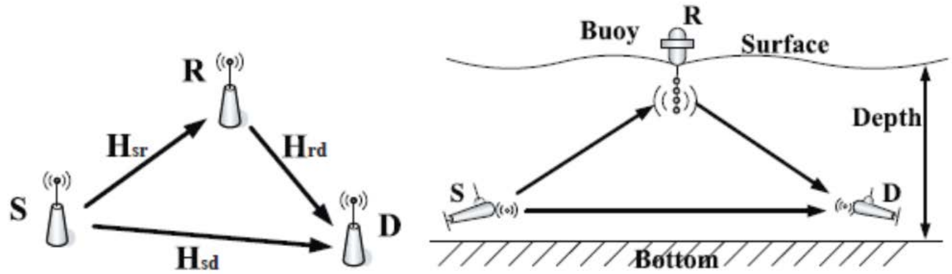


(a) Schematic illustration



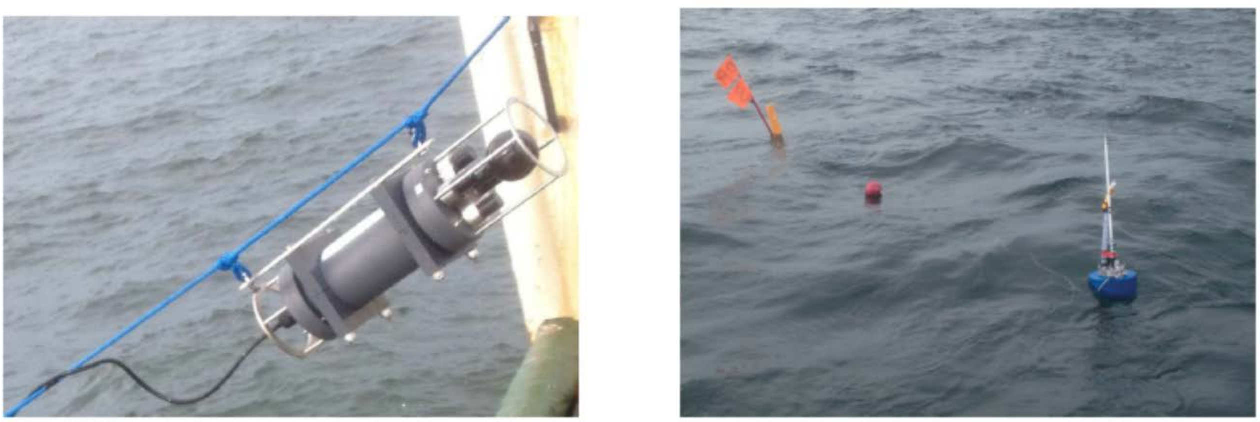
(b) Testbed picture

Figure 2. The experimental setup for power amplification tests with a transducer submerged inside a water tank



(a) (b)

Figure 3: (a) A generic setup of three-node cooperative communication; (b) Application in an underwater acoustic system.



(a) Modem (b) Buoy

Figure 4. The OFDM-modulated dynamic coded cooperation experiment, May 2013. (a) The OFDM modem before entering the water during deployment; (b) The buoy after being deployed

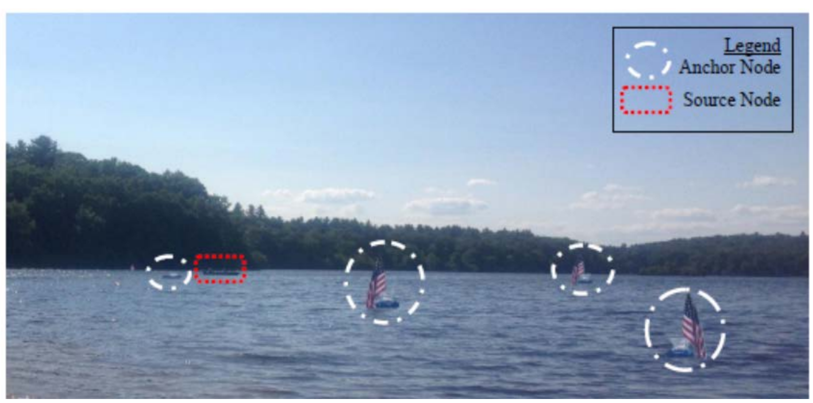


Figure 5: An image taken during a lake test for the On-Demand Asynchronous Localization (ODAL) algorithm developed at UCONN

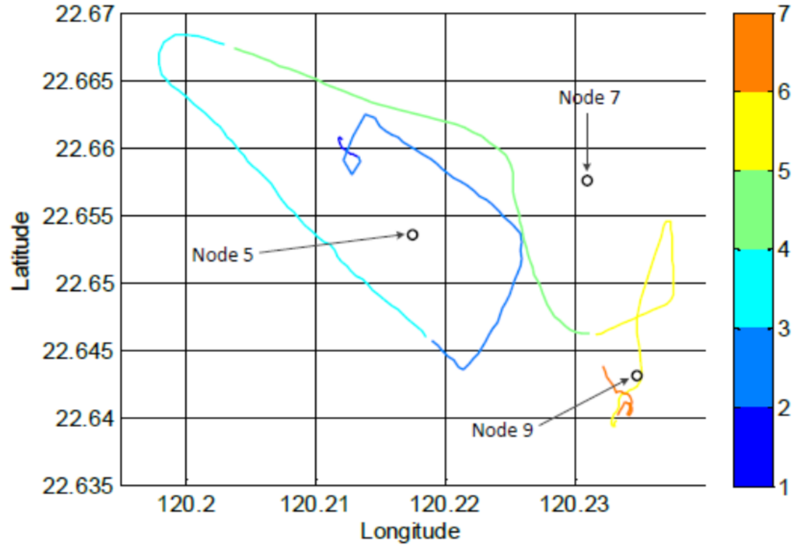
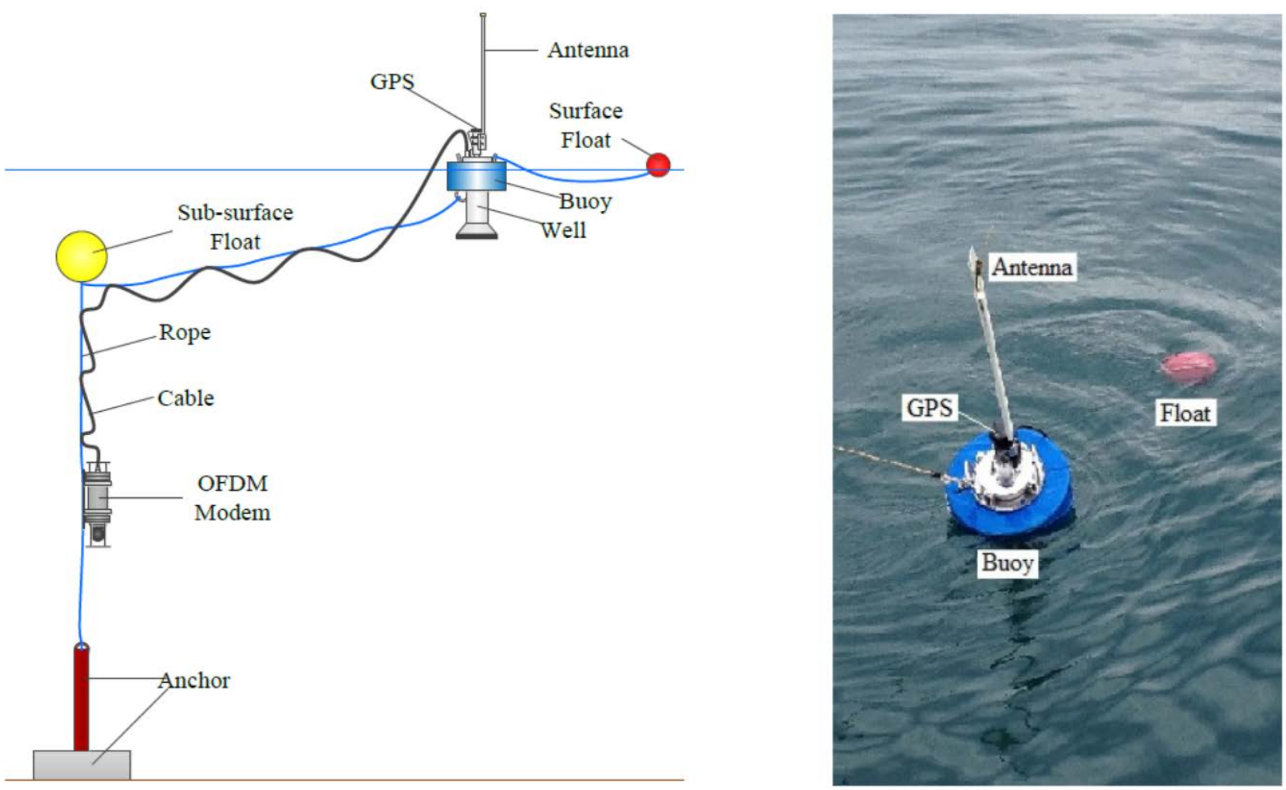
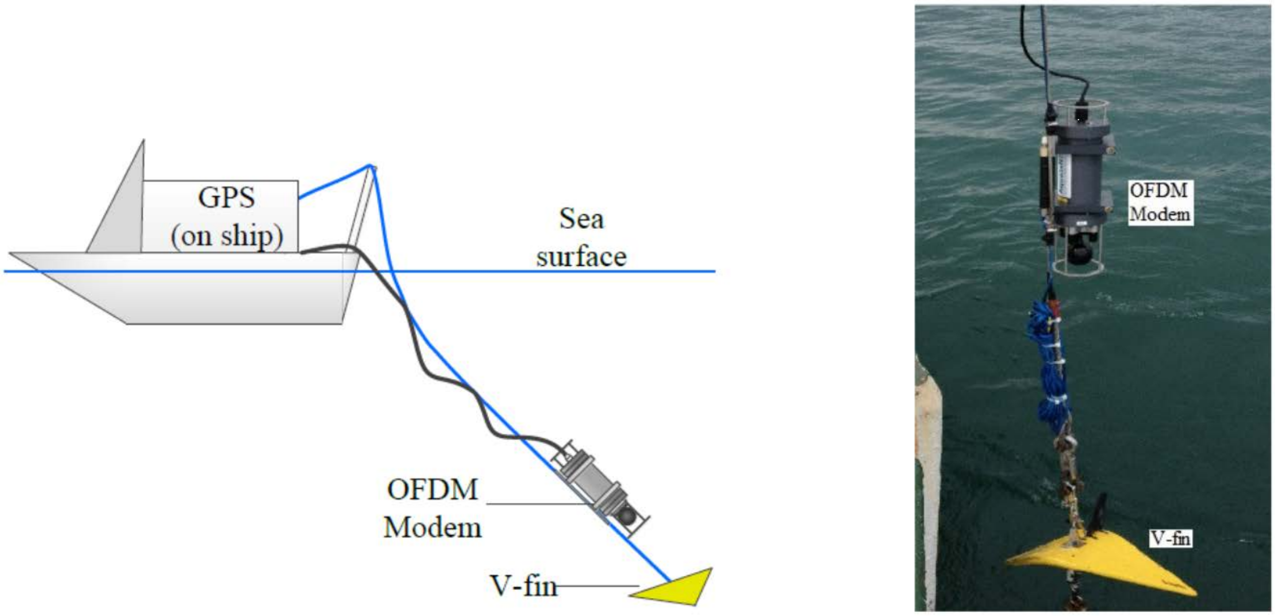


Figure 6: A localization test has also been carried out, where three surface nodes listen to the message from one mobile node, and try to estimate its position.



(a) Illustration (b) Deployment

Figure 7: Deployment of a stationary node during the Taiwan test.



(a) Illustration (b) Deployed node

Figure 8: Deployment of a mobile node during the Taiwan test.

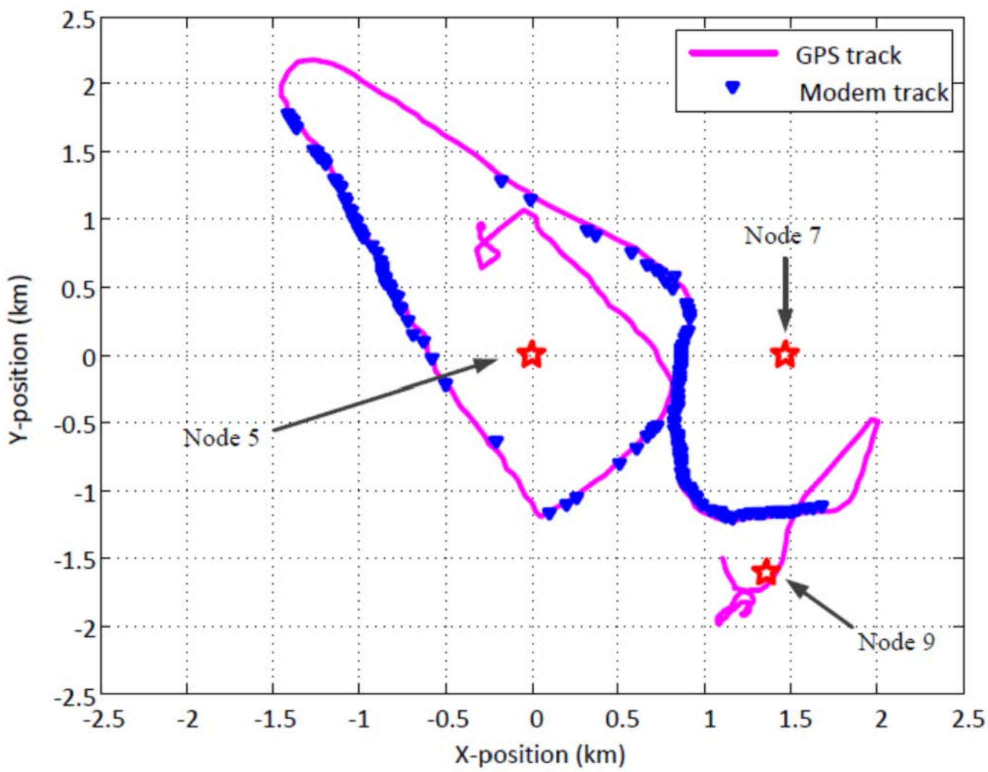


Figure 9: Comparison of the estimated track and the GPS track during the Taiwan test.